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THEMATIC DOSSIER
SMALL SCIENCE: PERSPECTIVES ON CONTEMPORARY SMALL-SCALE RESEARCH

Introduction
Why Small Science

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Is it possible today for a small research team to do excellent work with modest means? It does not seem so. Institutions such as CERN, the European Organization for Nuclear Research, the transnational laboratory of high-energy physics based in Geneva, loom large in the landscape of contemporary science. CERN represents a large-scale mode of research that mobilises vast resources and adopts the industrial division of labour. Along with observatories like LIGO (Laser Interferometer Gravitational Wave Observatory), telescopes like the James Webb (NASA), or supercomputing projects like Destination Earth, aimed at producing a digital twin of the Earth (EC-ESA-Eumetsat-ECMWF), organizations like CERN demand strong political will and sustained media support.[1] In comparison, the

[1] Jon Agar, *Science in the Twentieth Century and Beyond* (Cambridge: Polity, 2012).

work by small teams of researchers who do not require sophisticated equipment appears insignificant. As the editors of the *European Journal of Physics H* asked rhetorically in 2021: "Are prospects dwindling for big breakthroughs from small experiments?."[2] Physicist Gianfranco Giudice concurs that Big Science is "an irreplaceable instrument of modern science" and that we are immersed in an irreversible historical process: "Wherever science makes progress, sooner or later the need for large and expensive instruments, for goal-driven organized undertakings, for tight collaboration of scientists educated and trained in different disciplines, will arise."[3]

These are not recent concerns. Through the Cold War and beyond, the contrast in scale between modes of research has been expressed primarily through the categories of *Big Science* and *small* or *little science*. In the 1960s, historian of science Derek J. de Solla Price bolstered this vocabulary in a highly influential book that sought to analyse "what it is that is essentially new in the present age of Big Science, distinguishing it from the former state of Little Science." The relation between the two categories was, from the outset, very asymmetrical: while Big science was "new and shining and all-powerful," little science was "the former state of affairs" that "was once our form of life."[4] This rhetoric was highly effective. At the same time that it recognised its existence, it sealed the subsidiary meaning of a category hardly used before. In the history of science, we find numerous analogous situations. Robert Kohler demonstrated how, as laboratory science was becoming dominant in early twentieth century biology, field biologists assimilated laboratory values and practices, although without losing their naturalist essence.[5] In another instance, promoters of satellite remote-sensing technology presented it in the 1960s as a "rational, modern and efficient" scientific tool to differentiate it from, and eventually replace, what they described as "old-fashioned, qualitative and second-class" aerial photo-interpretation.[6] Similarly, in the first decade of the twentieth century, the proponents of relativity and quantum theory opposed their modern physics to a newly created "classical" physics: "classical and modern physics were co-creations, mirror image twins of the fault line between the physics of the past and

[2] James D. Wells and Michael Eckert, "EPJH Editorial," *The European Physical Journal H* 46, no. 1 (2021): 12-3.

[3] Gian Franco Giudice, "Big Science and the Large Hadron Collider", *Physics in Perspective* 14, no. 1 (2012): 95-112.

[4] Derek J. de Solla Price, *Little Science, Big Science… and Beyond* (New York: Oxford University Press, 1963), xvi and 2; D. J. de Solla Price, *Science Since Babylon* (New Haven, CT: Yale University Press, 1961). K. Brad Wray, "A foundational text in scientometrics," *Metascience* 32, no. 2 (2023): 235-9.

[5] Robert E. Kohler, *Landscapes and Labscapes. Exploring the Lab-Field Border in Biology* (Chicago: The Chicago of University Press, 2002).

[6] Gemma Cirac-Claveras, "Re-imagining The Space Age: Early Satellite Development from Earthly Fieldwork Practice", *Science as Culture* 31, no. 2 (2022): 163-186.

that of the future."[7] We argue that big and small science sit on each side of the fault line between modes of contemporary research.

Narratives about the obsolescence of small-scale research are now under question. On the one hand, historians of science and technology have begun paying attention to little science. Already in 2001 Steven Shapin echoed some scientists who were "violently critical of what they take to be […] the tyrannizing and stultifying effects of bureaucratization in science [and of] the hegemony of Big Science at the expense of Little."[8] David Edgerton has also noticed that we have shifted attention "from the new to the old, the big to the small, the spectacular to the mundane, the masculine to the feminine, the rich to the poor"[9]—and, we could add, the universal to the situated, the global to the local. On the other hand, these appraisals have been accompanied by a renewed appreciation of artisanal and craft knowledge and by a broad criticism of spectacular and accelerated science, to which several authors have opposed new, allied categories, such as frugal, slow, minor, or thrifty science. Why this academic interest on modest research? How do these views on the organization of contemporary research relate to what we know about the historical development of science and technology?

This dossier on small-scale research stems from an international workshop held at the Institute for History of Science of the Universitat Autònoma de Barcelona in February 2023. The workshop was intended to test and discuss the hypothesis that scientific knowledge is not just produced by means of large, expensive, hierarchically managed projects, but also by means of small, cost-effective, and often very local teams. The dossier aims to illuminate a key but overlooked feature of contemporary science by critically exploring some of the historical strands that converge in current small-scale research practices and re-examining their relationship with large-scale research.

The papers included in the dossier seek to explain various forms of networks, processes, and aims involved in promoting, developing, and maintaining small-scale research in different historical contexts. The three central papers engage in a conversation on the ideology, practicality, feasibility, and sustainability of small science, looking at the relation of quantum technologies with past artisanal practices and cultures (Phillips), the development of frugal technologies (Shekhar and Bhaduri), and the ethics of big and small research (Aibar). This introductory paper gives an overview of the category and of the relevant literature, trying

[7] Richard Staley, "On the Co-creation of Classical and Modern Physics," *Isis* 96, no. 4 (2005), 530-58, on 533.
[8] Steve Shapin, "How to be Antiscientific," in *The One Culture? A Conversation about Science,* eds. Harry Collins and Jay A. Labinger, 99-115 (Chicago: The University of Chicago Press, 2001), 113.
[9] David Edgerton, *The Shock of the Old. Technology and Global History since 1900* (London: Profile Books, 2006), xv.

to unveil the tacit political and epistemological hierarchies of research at different scales. Finally, the closing comment (Aubin) provides a critical perspective on the issue and the category "small science." Altogether, this issue contributes to our understanding of small science practices for knowledge production in different ways, shedding light on issues about power, resources, control and narratives.

A Subordinate Tacit Category

The historical categories we use to analyse science and technology are not natural and given, but rhetorical conceptual tools that have a history of their own. Some of these histories have been carefully retrieved, and we have detailed accounts of the historical formation of categories such as fundamental research, applied science, curiosity-driven science, open science, data-driven science, and even Big Science.[10] However, in the shadow of more powerful categories, small science has generally been considered by historians a minor category not worth the same attention as any other. The use of the coproduced categories of Big and small science is revealing of an epistemological and political hierarchy. We have yet to analyse how the demarcation between both categories has been strengthened or debilitated throughout the Cold War and beyond, and also beyond the physical sciences. This goes beyond our aims in this issue, but this asymmetry is to be kept in mind as we unfold the subsidiary meaning of small science.

Even though the rise of large-scale research is already apparent in the interwar years, the origins of the category Big Science are usually traced back to the scientific, industrial, and military projects of Second World War.[11] It was in the United States, in the postwar years, that some of the scientists who had led the war effort introduced the category in the public discourse on science and politics. Merle A. Tuve sought relief from the pressures of big science at the Department of Terrestrial Magnetism of the Carnegie Institution, a place which had "no external allegiance or obligations, no students, stockholders, voters,

[10] Sabine Clarke, "Pure Science With a Practical Aim: the Meanings of Fundamental Research in Britain, circa 1916–1950", *Isis* 101, no. 2 (2010): 285-311; Robert Bud, "'Applied Science': A Phrase in Search of a Meaning," *Isis* 103, no. 3 (2012): 537-45; Jon Agar, "The Curious History of Curiosity-driven Research," *Notes and Records of the Royal Society of London* (2017) doi:10.1098/rsnr.2017.0034; Sabina Leonelli, *Philosophy of Open Science* (Cambridge: Cambridge University Press, 2023); James H. Capshew, Karen A. Rader, "Big Science: Price to the Present," *Osiris*, 7 (1992): 3-25; Bruno Strasser, Data-driven Sciences: From Wonder Cabinets to Electronic Databases, *Studies in History and Philosophy of Biological and Biomedical Sciences* 43, no. 1 (2012): 85-87.

[11] Jeff Hughes, *The Manhattan Project. Big Science and the Atom Bomb* (Duxford: Icon Books, 2002); Alexei Kojevnikov, *Stalin's Great Science. The Times and Adventures of Soviet Physicists* (London: Imperial College Press, 2004); Ryan Dahn, "Big Science, Nazified? Pascual Jordan, Adolf Meyer-Abich, and the Abortive Scientific Journal *Physis*," *Isis* 110, no. 1 (2019): 68-90.

or other special group to serve."[12] In May 1959, he asked the participants in a symposium on basic research at the Rockefeller Institute in New York whether science was "too big for the scientist" and expressed his concern for the negative effects of the use of sophisticated, expensive equipment: "It is the unadorned mind of man, and not the fanciful instruments man conceives, that produces all of the beautiful in science."[13] Physicist Alvin M. Weinberg, director of the Oak Ridge Laboratory, regarded high-energy accelerators, rockets and nuclear reactors as "symbols of our time just as surely as […] Notre Dame [is] a symbol of the Middle Ages," yet he was actually concerned about their reliance on the media, money, and administration.[14]

Two things are worth noting about this. First, Big Science emerged as a concept in the specific context of the United Sates of the 1960s to refer to some scientific practices of the postwar period. This is therefore a very situated category. Historians have shown that it served to project national power through a specific form of science and technology.[15] The universality of the category needs be questioned. In the sciences, fields such as geology, meteorology, soil sciences, or solid state physics were not big in the same sense that high-energy physics was—not to speak about the social sciences or non-Western contexts. When we talk about Big science today, then, we must have in mind that it doesn't have the same meaning it did when people talked about it in the 1960s; consequently, when we talk about small science today, it cannot have the same meaning it may have had back in the 1960s.

Second, none of the authors who discussed the rise of large-scale research during the Cold War bothered to define small science but "as lacking one or another characteristic of Big Science, or as some vague historical predecessor."[16] This is a story about a category that creates a subordinate one, in order to establish and perpetuate itself as the valid and legitimate category. No comprehensive studies yet exist on the boundary work needed to create a public image for (Big) science by contrasting it favourably to other ways of practicing (small) science, and how these demarcations were maintained over the years, how they were nuanced in contexts other than US Cold War physics, or the political implications they had. Small science is thus a tacit, negatively defined category, and we should perhaps

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[12] Jessica Wang, "Physics, Emotion, and the Scientific Self: Merle Tuve's Cold War," *Historical Studies in the Natural Sciences* 42, no. 5 (2012): 341-88, on 349, quoting a 1946 memorandum by Tuve.

[13] Merle A. Tuve, "Is Science Too Big for the Scientist?", *The Saturday Review* (1959): 49-52, on 48; also, on 51: "creative work is nearly always done with limited resources and under difficult conditions."

[14] Alvin M. Weinberg, "Impact of Large-Scale Science on the United States," *Science*, 134, no. 3473 (1961): 161-4: "we must not allow ourselves, by short-sighted seeking after fragile monuments of Big Science, to be diverted from our real purpose, which is the enriching and broadening of human life." A. M. Weinberg, *Reflections on Big Science* (Cambridge, MA: MIT Press, 1967).

[15] P. Charitos, T. Arabatzis, H. Cliff, G. Dissertori, J. Forneris, & J. Li-Ying, eds., *Big Science in the 21st Century. Economic and Societal Impacts* (London: IOP Publishing, 2023).

[16] Capshew and Rader, "Big Science: Price to the Present," 4.

not be surprised that it has not attracted historiographical attention, so abducted historians have been by the epistemic supremacy of Big science. There are numerous studies on the growth of contemporary science, as witnessed by the volume edited by Peter Galison and Bruce Hevly in 1992, which includes an introductory bibliography with more than a hundred references, or the recent volume edited by P. Charitos *et al*. in 2023, but there is no comparable study of small science.[17]

This occultation notwithstanding, the category was implicitly used with a rather stable meaning during the second half of the twentieth century. We have performed a summary review and analysis of papers, news and editorials in two major science journals, *Nature* and *Science*. A search for the keywords "small science" or "little science" returns some 800 results. A small percentage of the results are redundant, and about half of them are irrelevant, either because the focus is on the adjective (as in "small science schools") or because they use the labels (especially small science) as a synonym of nanoscience. The survey does show, however, that small or little science were categories consistently if vaguely deployed by scientists, science administrators, and journalists, mostly in a defensive or reactive way. For the period 1970–1990 the major theme of these references was the funding conflict between big and small science projects, expressed either as a conflict between disciplines (physics and biology, for instance), or between subfields of the same discipline (high-energy and solid state physics).[18] Biologists used the category to bemoan the shift of research funds into the Human Genome Project, and it was also used by physicists upset by accelerator enthusiasts "laying claim to achievements that properly belong to small science," as with magnetic resonance imaging.[19] From the mid-1990s there is a discernible change in tone: big science and small science are discussed on an equal footing, and small science projects are vindicated, sometimes in connection with, but not dependent upon, big science projects.[20]

[17] Peter Galison and Bruce Hevly, eds., *Big Science: The Growth of Large-Scale Research* (Stanford: Stanford University Press, 1992); Charitos et al., *Big Science in the 21st Century*. See also Arnold Thackray, ed. *Science after '40*, *Osiris* 7 (1992): ix + 307.

[18] David Lindley, "Congress Gives Supercollider Easy Round but Worries About Cost", *Nature* 326 (1987): 633; Nature editorial, "Fighting Wrong Battles", *Nature* 332 (1988): 382; Constance Holden, "Small Science Squeeze," *Science* 225 (1992): 1507; Nature Special Correspondent, "The EMBO Question Debated", *Nature* 224 (1969): 406-7; Robert Walgate, "Another blow to UK physicists", *Nature* 308 (1984): 390; Bruce M. Alberts, "Limits to Growth: In Biology, Small Science is Good Science", *Cell* 41 (1985): 337-8. Daniel Kevles, "Big Science and Big Politics in the United States: Reflections on the Death of the SSC and the Life of the Human Genome Project," *Historical Studies in the Physical and Biological Sciences* 27, no. 2 (1997): 269-97; Joseph D. Martin, *Solid State Insurrection. How the Science of Substance Made American Physics Matter* (Pittsburgh: University of Pittsburgh Press, 2019).

[19] Christopher Willis, "Our Genetic Legacy," *Nature* 364 (1993): 113; David C. Chaffee (1991), "Can Big Science Claim Credit for MRI?," *Science* 253 (1991): 1204.

[20] See Daniel E. Koshland, "To Lift the Lamp Beside the Research Door", *Science* 233 (1986): 609 for an early indication of change; Jeremy Berg, "Science, Big and Small", *Science* 358 (2017): 1504;

How has the historical and historiographical value of small science changed? To understand the resignification of this category, it is not enough to look at contemporary science: we have to go further back in time.

Invisible Practices

The naturalisation of the growth of science as an historical development has not just eclipsed contemporary small science. It has also distorted our perception of modern science in at least two related ways: by ignoring the global dimension of modern information orders and by downplaying the importance of artisanal and craft knowledge.[21]

Modern science was built on widespread knowledge networks involving many different actors. The study of these information orders has shown the planetary range of the newtonian revolution and has questioned the image of Newton as a secluded scholar, an image he carefully promoted himself.[22] It has also led to the recognition of ancestral categories such as Big Sciences and small sciences. The former would embrace "a good part of stellar and planetary astronomy, cartography, mathematical and descriptive geography (including what we would now call anthropology and ethnography), natural history, meteorology […] pharmacy and medical botany, and some parts of mixed mathematics," while the latter would include "virtually all of experimental philosophy, anatomy and surgery, most of 'pure' mathematics, and a surprising number of the classics of the Scientific Revolution."[23] Science has long established deep connections with the large world of business and commerce. As Dominique Pestre concludes: "the world of business, commerce and production has always been a major resource for the development of knowledge and science."[24] Science was anything but small before the Second World War, at least not in the

Nature Editorial, "Embrace All Sizes," *Nature* 566 (2019): 295, commenting on Lingfei Wu, Dashun Wang, James A. Evans, "Large Teams Develop and Small Teams Disrupt Science and Technology," *Nature* 308 (2019): 378–382. Compare Michael Park, Erin Leahey, Russell J. Funk, "Papers and Patents are Becoming Less Disruptive Over Time", *Nature* 613 (2023): 138–144; Max Kozlov, "'Disruptive' Science Has Declined – Even as Papers Proliferate," *Nature* 613 (2023): 225.

[21] John V. Pickstone, *Ways of Knowing: A New History of Science, Technology, and Medicine* (Manchester: Manchester University Press, 2001).

[22] Simon Schaffer, *The Information Order of Isaac Newton's Principia* (Uppsala: Uppsala University, 2008).

[23] Steven J. Harris (1998), "Long-distance Corporations, Big Sciences, and the Geography of Knowledge", *Configurations* 6 (1998): 269-304, on p. 295.

[24] Dominique Pestre, "Savoirs et Sciences de la Renaissance à nos Jours. Une Lecture de Longue Durée," in Dominique Pestre and Christophe Bonneuil, eds. *Histoire des Sciences et des Savoirs. Vol. 3. Le Siècle des Technosciences* (París: Seuil, 2015): 461-85, on 474: "le monde des affaires, du commerce et de la production a toujours constitué une ressource majeure du déploiement des savoirs et des sciences". Cf. Lissa Roberts, Simon Schaffer, Peter Dear, eds., *The Mindful Hand. Inquiry and Invention from the Late Renaissance to Early Industrialisation* (Amsterdam: KNAW, 2007); Lissa Roberts and Simon Werrett, eds., *Compound Histories. Materials, Governance and Production* (Leiden and Boston: Brill, 2017).

implicit sense used by promoters of big science. For instance, beginning also as part of the political and commercial imperial project of the nineteenth century, efforts to integrate networks laid out decades or centuries earlier to create a permanent planetary observing network proliferated. Through these "knowledge infrastructures," taking Paul Edwards' term, the world as a whole was produced and maintained as both object of knowledge and unified arena of human action.[25] Yet, these global efforts to collect, process, share, store and use data, such as the International Polar Year, the International Geophysical Year, the Global Atmospheric Research Program, the International Geosphere-Biosphere Program, the World Ocean Circulation Experiment, and others that have followed throughout the twentieth century, are rarely considered as exemplary of Big Science—interestingly enough they are not framed as Big Data efforts either.[26] The fact that they were not paradigmatic big endeavours does not mean that they were small; if they were, it would be necessary to explain in what sense.

The second historiographical distortion has to do with the invisibility of the role of artisanal and craft knowledge. Invisibility may refer to the invisible nature of the artisanal knowledge itself, to the invisible work performed by actors, and to the processes of making invisible activities. The critique to the hegemony of contemporary big science relates to the relevance of such knowledge for the development of science. Again Pestre: "the savoir faire and artisanal and production knowledges have been (and still are) decisive in the emergence (and ongoing transformation) of science; this is particularly true for the culture of precision and experimental practices."[27] The rich literature surrounding artisanal forms of knowledge-making from the eighteenth and nineteenth centuries illuminates the complex lineage of current small-scale endeavours. As shown by Phillips' contribution to this issue, such work has pointed to the complicated ways in which small groups of highly skilled workers, typically engaged *in* and *across* very small working sites, were able to contribute at the cutting-edge of knowledge making. Of crucial importance in these accounts has been to show the ways in which these groups were on the one hand hugely impactful, but at the same time attempting to manage their ability work at the small scale. Moreover, the Eurocentric perspective has long been challenged by comparative history, transnational history, post-colonial studies and "multiple modernities" that have questioned the inevitability of secularization posited in modernity theory, and more recently the paradigm of global history. In various aspects,

[25] Paul N. Edwards, *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming* (Cambridge, MA: The MIT Press, 2010).

[26] On the history of Big Data practices see Elena Aronova, Christine von Oertzen and David Sepkoski, *Data Histories*, special issue of *Osiris* 32 (2017).

[27] Pestre, "Savoirs et Sciences," 472: "les savoir-faire, les savoirs artisanaux et de production ont été (et sont toujours) décisifs dans l'émergence (et la transformation continue) des sciences ; cela est notamment vrai pour la culture de précision et les pratiques expérimentales." Otto Sibum, "What Kind of Science is Experimental Physics?," *Science* 306, 1 October 2004: 60-1.

all these approaches are sympathetic to the study of small science research. Together with craft knowledge, invisible technicians, non-elites, gendered scientific practices, activist networks and indigenous knowledge, they are just examples of forms of small science that can be made visible when accounting for the global dimension of science.

In *Thrifty Science*, Simon Werrett discusses the early modern approach to "achieving a balance between spending and buying new and saving and making use of things," noticing that it seems to be "reemerging today." The twentieth century would not represent a turning point but an interlude: "While people in the late-twentieth century supposed that the future of science would be mostly 'big,' as we enter the twenty-first century, it seems that the future will also be small." Take space technology, which tends to be portrayed as a prototypical example of Big Science, involving state-funded huge spacecraft, hierarchical centralised management, large industrial contracts and associated gargantuan costs, often embedded within a Cold War era narrative of rivalry. The Apollo program, the Hubble Telescope or the International Space Station come to mind. Yet there are around 1700 private-owned small satellites orbiting the Earth. At least more than 130 of those satellites are tiny (the size of a shoebox), have been developed thanks to crowdfunding campaigns, use a GPS receiver to collect atmospheric data for weather forecasts, and can only be understood under the paradigm of global capitalism.[28] We can question, of course, to what extent producing and commercialising terabytes of data, with the infrastructures implied, can be labelled as small science—but certainly it is not the kind of Big Science that the scientists and advisors who coined the term in the 1950s and 1960s had in mind. Also, the use of GPS receivers, originally developed for other purposes and already mass-produced, illustrates that Werrett's thrifty practices have not disappeared but have been "obscured" by the growth of contemporary science: "Scientists have continued to make use of things ready to hand, to improvise, substitute, and shift."[29]

In the same way that historians have devoted substantial efforts to show the global reach and the industrial and economic dimension of science prior to the advent of big science, we need now to devote a comparable effort to show, conversely, the relevance of seemingly obscured practices in contemporary science. Because if going Big belonged to the imperial project and the colonisation of physics, embedded in United States-centric Cold War narratives, then going small belongs to the political project of recognizing the practices, networks, aims and processes that have been marginalised by these hegemonic discourses and historiography.

[28] Gemma Cirac-Claveras, "Trading with Weather. Governmental and Commercial Meteorological Satellites," *Entreprises et Histoire* 102, no. 1 (2021): 78-98.

[29] Simon Werrett, *Thrifty Science. Making the Most of Materials in the History of Experiment* (Chicago: The University of Chicago Press, 2019), on 194 and 196.

To present and discuss examples of small contemporary science was one of the aims of the workshop behind this dossier and would exceed the aims of this introduction. But we cannot but point out to two inspiring and illuminating cases. The first concerns atmospheric ozone. In 1985 J. C. Farman, B. G. Gardiner, and J. D. Shanklin published a seminal paper on the losses of stratospheric ozone. Sebastian Grevsmül has asked how could "a little known team with a relatively modest budget" beat NASA at the discovery of a hole in the atmospheric ozone layer.[30] He has subsequently extended the argument to the images produced by the small research team of the British Antarctic Survey, stressing the relative simplicity and stability of its instrumental arrangement:

> [They] knew how to build up trust in their data and hence their images with the help of regular instrument calibrations but also rigorous methodological consistency. The instrumental backbone of the ozone network, the Dobson spectrophotometer, named after its British inventor who produced the first total ozone measurements in Oxford during the 1920s, underwent few changes throughout its history. There was, in other words, very little friction involved, allowing researchers to create a highly robust data-set – without the necessity of making data of different instrumental origins compatible. . .and to speak thus with authority on Antarctic stratospheric ozone.[31]

While part of a large international project, the success of Farman's team was inextricably linked to its tiny size and its persistence in the face of apparently negative results, which almost got the project cancelled.[32]

Our second case displaying some of the key features of small science is the Dragonfly Telephoto Array, an observational astronomy project led by Roberto G. Abraham and Pieter G. van Dokkum. Together with a team of six to eight researchers, they have developed a robotic system connecting tens of 400 mmm telephoto lenses, as in a dragonfly eye. The array sweeps wide parts of the sky, revealing galaxy structures that are not visible to large telescopes, taking advantage of the fact that "several of the basic design trades that make large telescopes possible. . .define the fundamental systematic errors that make pushing to very low surface brightnesses so difficult." Here smallness worked to the advantage of the astronomers, allowing the detection of "ultrafaint substructures" in the nearby universe.[33]

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[30] Joseph C. Farman, B. G. Gardiner, J. D. Shanklin, "Large Losses of Total Ozone in Antarctica Reveal Seasonal ClOx/NOx Interaction," *Nature* 315 (1985): 207-210; Sebastian Grevsmühl, *La Terre Vue d'en Haut. L'Invention de l'Environnement Global* (Paris: Seuil, 2014): 280.

[31] Sebastian Grevsmühl, "A visual History of the Ozone Hole: A Journey to the Heart of Science, Technology and The Global Environment", *History and Technology* 33 (2018): 333-344, on 337.

[32] Paul Merchant, "'He Didn't Go Round the Conference Circuit Talking About It': Oral Histories of Joseph Farman and the Ozone Hole," in *The Silences of Science. Gaps and Pauses in the Communication of Science*, Felicity Mellor, Stephen Webster, eds. (London: Routledge, 2016), 31-47.

[33] Roberto G. Abraham and Pieter G. van Dokkum, "Ultra–Low Surface Brightness Imaging with the Dragonfly Telephoto Array," *Publications of the Astronomical Society of the Pacific* 126, no. 935

Dragonfly suggests that small science projects are not about doing the same with less, or having to make do with limited resources; rather, they are about using the optimal tools for the problem at hand. These effective ways of doing, seemingly going against the grain of big contemporary science, have enlarged our knowledge in significant ways, unveiling phenomena that would otherwise remain invisible. In a similar vein, the category small science may allow us to detect features of contemporary science that are not visible through other categories, particularly big science.

Naming Small Science

Along with Werrett's "thrifty science," several similarly proactive terms referring to small research practices have recently been proposed and deployed. This proliferation suggests a common historical and political concern among historians about the ever more apparent effects of accelerated research and innovation.

In her enquiry about the critical posthumanities, philosopher Rossi Braidotti has noted the existence of "underfunded, marginalized, ethically transformative, politically empowering" subjects, which she names "minor" science/knowledge to distinguish them from "royal" science/knowledge—"institutionally implemented, well-funded, sedentary, protocol-bound, compatible with the economic imperatives of advanced capitalism." The overlap with small science is as clear as intriguing. Not all small science projects need to be underfunded, yet many appear to be so when compared with bigger, better publicised projects.[34]

A similar concern with uncertainty, fragility and empowerment is evident in the work of philosopher and historian of science Isabelle Stengers. Against the disembedded knowledge characteristic of fast science, in *Another Science is Possible. A Manifesto for Slow Science* she argues for the careful consideration of what appears to be messy, "as something we have to learn to live in and think with." She characterises slow science "as the demanding operation that would *reclaim* the art of dealing with, and learning from, what scientists too often consider messy, that is, what escapes general, so-called objective, categories".[35]

Sebastián Ureta, who participated in the workshop, has discussed the scientific practice at the Centro Nacional del Medio Ambiente (CENMA), a derelict environmental chemistry laboratory in Santiago, Chile, in terms of "ruination."[36] Scientists at CENMA adhered to

(2014): 55-69, on 55 and 56.

[34] Rossi Braidotti, "A Theoretical Framework for the Critical Posthumanities," *Theory, Culture & Society* 36, no. 6 (2018): 31-61, on 47.

[35] Isabelle Stengers, *Another Science is Possible. A Manifesto for Slow Science* (Cambridge: Polity, 2018), 120.

[36] Ann Laura Stoler, "Imperial Debris: Reflections on Ruins and Ruination," *Cultural Anthropology* 23, no. 2 (2018): 191-219.

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"an alternative kind of scientific practice . . .always precarious [yet] well adapted to engage with impurity, resilient but fragile, and ethically entangled." He provides a close description of scientific work in conditions of material scarcity and utmost uncertainty:

> Ruination science as practiced in CENMA tried to obtain maximum results out of its limited material means. . .It accepted material recalcitrance, recognizing that some things cannot be known. Ruination science was creative and flexible, continually adapting practices and devices in order to fulfil its aims, even if such adaptation made it transgress stated rules of 'good,' conventional science. . .Ruination science was both strong and weak, managing to survive in a challenging environment beyond everyone's expectations but finally succumbing to the accumulated weight of its multiple precariousness.[37]

How does "ruination science" fit in a more general notion of small science, not limited to such extreme circumstances?

Manu Prakash, an engineer at Stanford University and founder of Prakash Lab, provides another perspective, that of a science practitioner. He has promoted the design and use of so-called frugal instruments, such as Foldscope, an Origami-based paper projection microscope, or Paperfuge, a low-cost centrifuge, amongst others. By removing cost barriers, frugal instruments are meant to create a broader user base in both science education and field work for science and medicine. A member of Prakash Lab, James Cybulski has characterised frugal science as "science practised in a context of limited resources" and defined frugal innovation as the simultaneous optimization of performance, cost, and scalability.[38] Frugality belongs in a secular intellectual tradition which resonates with other humble technologies and which Bhaduri and Jain explore in this issue.[39] In the history of technology, it relates to the study of use rather than innovation. In the history of political ecology and economic thought, it relates to downsizing, self-sufficiency, and degrowth, as popularised in the 1970s, amongst others, by Fritz Schumacher (*Small is Beautiful*), Dana Meadows (*Limits to Growth*), or Wendell Berry ("Think Little").[40] In the history of

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[37] Sebastián Ureta, "Ruination Science: Producing Knowledge from a Toxic World," *Science, Technology and Human Values* 46, no. 1 (2021): 29-52, on 48.

[38] James S. Cybulski, *Novel Low-Cost Tools for Science, Diagnostics, and Education* (PhD diss., Stanford University, 2015), 29: "As a rough order-of-magnitude comparison with existing solutions, the frugal solution should have similar relative performance (order 100), much lower relative cost (order 10−3), and much higher relative scalability (order 103)." James S. Cybulski, James Clements and Manu Prakash, "Foldscope: Origami-Based Paper Microscope," *PLoS ONE* 9, e98781; M. Saad Bhamla *et al*. (2017), "Hand-powered Ultralow-cost Paper Centrifuge," *Nature Biomedical Engineering* 1, 0009.

[39] Balkrishna C. Rao, "The Science Underlying Frugal Innovations Should Not Be Frugal," *Royal Society Open Science*, 6 (2019): 180421. http://dx.doi.org/10.1098/rsos.180421

[40] Fritz Schumacher, *Small is Beautiful. Economics as if People Mattered* (London: Blond & Briggs, 1973); Dana Meadows, *The Limits to Growth*, (New York: Universe Books, 1972); Wendell Berry, "Think Little," in Wendell Berry, *A Continuous Harmony. Essays Cultural and Agricultural*, (New York: Harcourt, 1972), 71-85.

architecture, it connects with renewing, transforming and reusing, powerfully present in the recent award of the prestigious Pritzker price to RCR Arquitectes (2017), a small firm in a small town in northern Catalonia, and to Lacaton & Vassal (2021), "whose rallying cry is: "Never demolish, never remove—always add, transform and reuse."[41]

In all these instances we recognise the effects on contemporary science of changes that may be more readily apparent in other fields of action and knowledge.

Scale Matters

How to interpret this proliferation of terms attentive to and concerned with small-scale knowledge practices? How do they relate to each other, and to action and change in the current political, epistemological, and ecological crisis? With the notion of small science comes the crucial question of scale, whether of time and space, of human collectives, or of data. However potentially misleading the modern dichotomies (science/technology, idea/thing, etc) might be, we still need to think through the relation between big and small. Drawing inspiration from ecological studies, Deborah R. Coen frames this debate in terms of "scaling." Each ecological phenomenon, she writes,

> has its own 'characteristic scale,' to be determined by observing the patterns that the phenomenon exhibits at a series of different scales. Because ecological scale is a measure of relative interdependence, the most informative scale for the study of a given phenomenon is not an a priori decision but a conclusion to be reached empirically.[42]

From this perspective, "it has become our responsibility to think big and small at once." In this way, the apparent conflict between different levels of thought and action can be resolved: "A focus on scaling disrupts the linear narrative of a push toward ever larger dimensions of thought."[43] Taking on that, one argument of this issue is that scientific practices inhabit at the intersection of multiple scales: by linking macro, meso-, and micro-scales of time, space, and social organization, they form the stable foundation of modern science (and modern social worlds, more generally).

[41] Celine Nguyen, "'Never Demolish. Always Transform, With and For the Inhabitants': Anne Lacaton delivers inaugural Jaqueline Tyrwhitt Urban Design Lecture,", <https://www.gsd.harvard.edu/2022/04/never-demolish-always-transform-with-and-for-the-inhabitants-anne-lacaton-on-urban-design-and-architecture/>

[42] Deborah R. I. Coen, "Big is a Thing of the Past: Climate Change and Methodology in the History of Ideas," *Journal of the History of Ideas* 77, no. 2 (2016): 305-21, on 310 and 311.

[43] Ibid.

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How does scientific research look like when examined on different scales of force, time, and social organization? Methodologically, navigating among different scales represents a critical challenge but it might offer an antidote to blindness on both sides, the big and the small. Against the idea of conflict and replacement, it has been argued that small science stands in a relation of complementarity with big science. In a problematic argument, austerity has been presented as a source of innovation and disruptive ideas: "[Large-scale analyses] must continue to draw from innovative, imaginative ideas and strategies, driven by gifted individuals with a passion for science." Fortin and Curry have studied the impact of individual university-based researchers as related to funding. They conclude that "impact was a deceleration function of funding" and that scientific impact was "only weakly limited by funding," suggesting that "funding strategies that target diversity, rather than 'excellence', are likely to prove to be more productive."[44]

Attention has been paid in this connection to the work of little science teams within bigger projects and institutions. Even accelerators can be "the small scale work of a few people," as in the MAX-lab facility in Lund, "a 'home-made' accelerator project, constructed in a step-by-step fashion and with no overarching schedule or budget determined from start to end." In his study on the politics of synchrotron light laboratories, Hallonsten has reflected on the resilience of small-scale work:

> Small science was never swallowed nor completely outmanoeuvred by big science. It was in fact quite the opposite – when the Cold War wound down, small science made a comeback of sorts, with biology and life sciences taking the leading role as the spearhead in scientific benefit to society. But sophistication and collectivization of science and the increasing dominance of 'projects' and 'teams' . . .has made also small science increasingly dependent on centralized organizational constructs and technically advanced infrastructure.

In a significant reversal of the classical argument of displacement, Hallonsten has recently argued that what he deems "transformed" Big Science, "more attuned to the expectations and needs of current society. . .is essentially small science that uses big machines operated by big organizations, with the help of big politics."[45] In her work on Bevalac, a project of the Lawrence Laboratory in Berkeley, Catherine Westfall distinguishes between grand, modest and *mezzo* science, and argues for the importance of attending to the relation amongst different scale projects, rather than simply size.[46]

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[44] Jean Michel Fortin and David J. Currie, "Big Science vs. Little Science: How Scientific Impact Scales with Funding," *PLOS One* 8, no. 6 (2013): e65263.

[45] Olof Hallonsten, *Small Science on Big Machines: Politics and Practices of Synchrotron Radiation Laboratories* (Lund: Research Policy Institute, 2009); Olof Hallonsten, *Big Science Transformed. Science, Politics and Organization in Europe and the United States* (Cham: Palgrave Macmillan, 2019).

[46] Catherine Westfall, "Rethinking Big Science. Modest, Mezzo, Grand Science and the Development

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Work on peripheral accelerators has finally shown that old, central equipment can find new, unexpected uses upon relocation. *Cyclotron*, a documentary film by Jahnavi Phalkey (2020), "tells the story of the kind of science that is often ignored by chroniclers, done in a relatively small institution, unpeopled by the big names." The nuclear scientists trained at Chandigarh may pursue their careers in bigger high-energy labs, suggesting a role for small-scale practices within larger scientific collaborations.[47]

Conclusion

In the second half of the twentieth century, the rise of large-scale research, and the corresponding historical attention it claimed, eclipsed small-scale research. In the first decades of this century, this narrative of obsolescence and extinction has lost traction. The historiography of modern science has argued the relevance of artisanal and craft practices, while a number of authors have proposed new, related categories that strongly suggest the persistence of modest research practices. The historical argument that scientific practices cannot but become large-scale organized efforts is up for revision, as we acknowledge forms of research that do not seek ever increasing instruments and budgets.

Our preliminary analysis of small science is not to be read, however, as an apology. Small science remains an elusive if useful term. It is continuously used and it is easily recognisable, even though its meaning may not be clear to all, or may not be the same for all. We acknowledge that scale and infrastructure are often related in ways that are difficult to disentangle. A start-up that manages to launch a cube-satellite thanks to crowd-funding might be labelled as small science; but when the start-up grows and manages to launch hundreds of satellites, mobilizes a huge capital, and distributes terabytes of weather data all over the world, is still fair to label it as small science? In what sense hundreds of distributed small satellites are smaller than one big satellite? No science, no matter how small, is carried out in isolation. Scientists need markets, funding, people, materials, communication, networks. Are these infrastructures small? Can we, then, classify these endeavours as small science? In the same sense, we need to set aside small groups doing conventional science. They might be small but use powerful computers, have large state or private networks of

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of the Bevalac, 1971-1993," *Isis* 94, no. 1 (2003): 30-56; cf. Catherine Westfall and Lillian Hoddeson, "Thinking Small in Big Science: The Founding of Fermilab, 1960-1972,", *Technology and Culture* 37, no. 3 (1996), 457-92.

[47] Janhavi Phalkey, quoted in Barkha Kumari, "The Unbelievable Story of the World's Oldest Cyclotron," *VICE* 13/11/2020 https://www.vice.com/en/article/wx8d8n/the-worlds-oldest-cyclotron-in-india-now-in-a-film; Jahnavi Phalkey, *Cyclotron*, self-produced documentary film, 2020; Usha Raman (2020), "'Cyclotron' – a Tribute To the Quiet Work of India's Unsung Scientists," *The Wire Science*, 07/11/2020; https://science.thewire.in/the-sciences/jahnavi-phalkey-cyclotron-unglamorous-punjab-university-science/.

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support, funding…They can be seen as the scientific version of a more general drift caused by the ubiquity of mobile phones and computers: start-ups and small new companies that can operate with very few workers and modest means (but with top quality technology).

We acknowledge the vagueness of the category while valuing the interpretive flexibility it affords, and the way it allows us to engage with different fields of knowledge. We therefore think it is worth probing its uses and meanings. Amongst the reasons for our interest are the association with modest practices in architecture and the arts, connected with sustainability and a resistance to the dominant, capital-driven emphasis on innovation and growth; the desirability or the need for a diverse research system, consisting of different, interrelated modes of research; and the reaction to historical narratives that silence this diversity and support hegemonic forms of research and power. The study of small science may illuminate epistemic, disciplinary, and social hierarchies, and bring to the fore networks of invisibilised actors, sites of production and activities. We think there is much to be learnt by looking at contemporary science as consisting of a richly diverse research ecosystem, of which the smallest elements, labelled as "small science," have a crucial role to play.

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